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Experimental Results for Capillary Looped Pipe Applied to Direct Cooling Method

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The heat transport characteristics of capillary looped pipes are obtained from experimental results. Both indirect-cooling and direct-cooling capillary looped pipes were tested. An indirect-cooling looped pipe was tested to determine the flow direction of the working fluid and the relationship between the liquid charge quantity and the heat transfer characteristics. Tests show that using the direct-cooling configuration is superior to the indirect-cooling configuration.

Nomenclature

Kij = thermal conductance between i and j
Q = heat generation rate
ΔT = temperature difference between the evaporator and the condenser

Introduction

FIELD effect transistor (FET) chips have been used to construct high-power amplifiers needed for communications satellites. However, cooling must be considered because FET chips are quite small, but generate large amounts of heat. Embedding heat pipes within the equipment panels is an effective temperature control method for conventional low-power FET-based amplifiers. However, the heat generated by the chips cannot be transferred effectively to the panel due to the high thermal resistance of the interface between the FET substrate and amplifier housing. A better heat control scheme is needed if the output power of the amplifier is greatly increased.

Direct heat pipe cooling, in which the heat source circuits are immersed in the working fluid have been investigated.[1] Heat from the devices is carried to the substrate and the chip package where it is taken up by the evaporating fluid and transported to the heat sink. The condensed liquid returns to the evaporator through the wick attached to the inner surface of the package. For high-power FETs, however, the size of the FET package has to be larger than structurally needed to achieve a sufficiently high-heat dissipation rate. Thus, it is difficult to mount the required number of FETs within the area provided on the equipment panel. One proposed solution uses capillary looped pipes and direct cooling,[2] because this arrangement offers higher heat transfer rates. This solution makes it possible to minimize the size of the package because the heat from the high-power FETs can be removed by connecting the capillary loops to the satellite's embedded heat pipes.

The heat transport characteristics of direct-cooling capillary loops have not been clarified. Thus, this study examines the circulation of the working fluid as determined by the location of the evaporator relative to the condenser section. The thermal conductance of a standard direct-cooling capillary loop is obtained. In addition, a dual-looped pipe of the large boiling pressure type is tested to obtain its thermal conductance.

Experiments

We carried out three experiments to achieve the following goals: 1) determinable circulation direction of the working fluid, 2) find a relationship between the charge quantity of the working fluid and the thermal conductance, and 3) estimate the thermal conductance of a direct-cooling capillary looped pipe.

Both goals 1 and 2 were realized by testing an indirect cooling configuration because this configuration makes it easy to change the amount of the working fluid and the location of the heater.

Indirect Cooling Configuration

The loop was devoid of any wick material and was made of smooth-bore tubing. The pipe was a 400-mm-long copper tube with an i.d. of 2 mm. This provided a flow passage for the vapor transporting the heat to the condenser and returning the condensed liquid to the evaporator. In the condenser section, a plate cooled by pipes carrying water was attached to the capillary loop. The working fluid of the loop was CH_3CClF_2 (HCFCs 142b). After the working fluid was injected into the evacuated pipe, the pipe were sealed. The boiling temperature of the working fluid is -9.7°C under atmospheric pressure. The charge quantity of the working fluid was set at 20, 40, and 80% of the internal volume. For example, when the pipe was entirely occupied with the liquid of X g in weight, the 0.2% charge rates were decided by

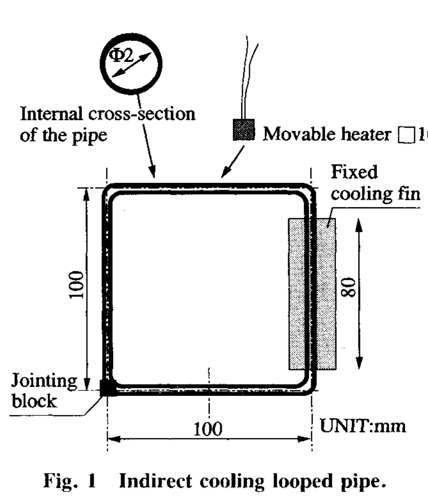

Fig. 1 Indirect cooling looped pipe.

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injecting the liquid of $0.2 \cdot X$ g in weight. A silicon rubber heater with a heat generation area of 10 × 10 mm was used. The heater was stuck to a 10- × 10-mm copper plate soldered on the outside wall of the pipe at various locations. The configuration of the indirect-cooling looped pipe is shown in Fig. 1.

Experimental Apparatus and Procedure

The capillary looped pipe was covered with silicon rubber sheets to reduce heat loss from the pipe surface. The heat generation rate was estimated by using the difference in temperature between the inlet and the outlet cooling water. The evaporator and condenser sections lay on the same horizontal plane to within an accuracy of ±0.1 deg. Copper-Constantan-type thermocouples were attached to the copper tubing wall to measure the temperature of the capillary loop. The experimental setup is shown in Fig. 2. The condenser section of the pipe was fastened with bolts on a fixture that allowed the height of the condenser to be fixed accurately. The fixture was also used to support the two direct-cooling looped pipe configurations.

Relationship Between the Charge Quantity of the Working Fluid and the Thermal Conductance Between the Evaporator and the Condenser

The indirect-cooling looped pipe was used to examine the effect of the quantity of working fluid. Figure 3 shows the temperature measurement points. The temperature of the pipe was measured at 5 points for working fluid charges of 20, 40, and 80% of the internal volume of the pipe. The measured temperatures are shown in Figs. 4, 5, and 6, respectively. The temperatures measured at point e with 20 and 80% charges are higher than those measured at points b or c. This indicates that with these charges there is no mass circulation, and heat transfer occurs by the heat pipe mode. There is, however, some change noticeable with the 40% charge at a heat flux of about 1.5 W/cm². The temperatures at points b and c rapidly surpass those at e, indicating that the initial heat pipe mode is replaced by the circulation mode. The relationship between the heat flux and the thermal conductance is shown in Fig. 7. The thermal conductance is plotted as a function of the heat generation rate and the temperature difference between the evaporator and the condenser using the relationship $K = Q/\Delta T$. It is obvious that the 20% charge yields the highest thermal conductance at low heat fluxes from 1 to 3 W/cm². The relatively low quantity of working fluid offers the vapor relatively little resistance, thus promoting effective cooling through high rates of mass transfer. At high heat fluxes, however, the quantity of vapor is insufficient so that the exit temperature (point a) climbs very quickly.

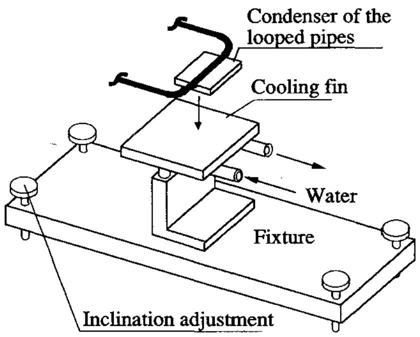

Fig. 2 Experimental configuration.

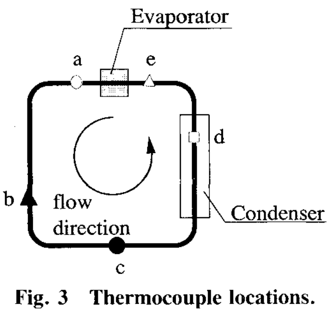

Fig. 3 Thermocouple locations.

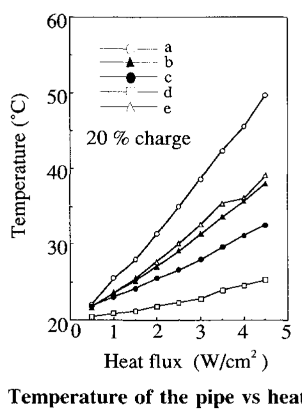

Fig. 4 Temperature of the pipe vs heat flux.

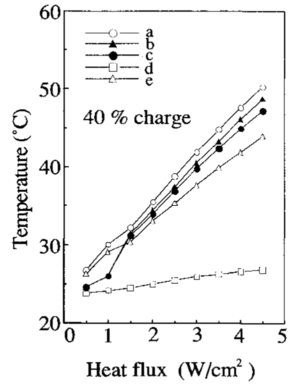

Fig. 5 Temperature of the pipe vs heat flux.

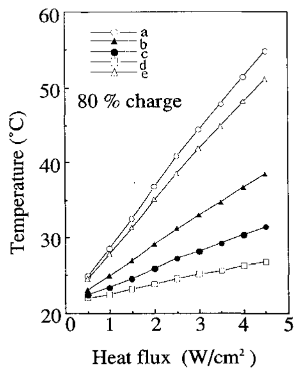

Fig. 6 Temperature of the pipe vs heat flux.

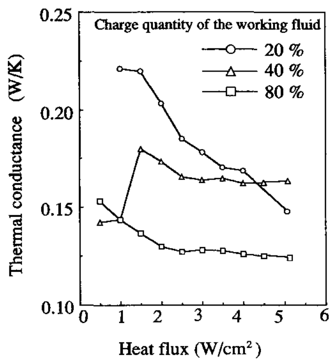

Fig. 7 Thermal conductance vs heat flux.

As the heat flux increases above 3 W/cm^2, the 40% charge yields the highest thermal conductance. Therefore, we conclude that of the three charges examined the 40% charge provides the best overall cooling.

Circulation Direction of the Working Fluid

The circulation direction of the working fluid was obtained by changing the location of the heater. The charge rate of 40% was adopted based on the results of the indirect cooling experiments.

The temperature of the pipe was measured at 8 locations (identified as a, b, . . . h) for five evaporator locations (identified as 1, 2, . . . 5). The results are given in Table 1. Figure 8 shows the heater locations and the temperature measurement points. When the evaporator is located at 1, the temperature drops in the order a-h-g-f-e. The interpretation is that mass transfer occurs in the same order, i.e., counterclockwise. Conversely, with the evaporator located at point 2, the circulation pattern is clockwise. When the evaporator is set at point 5, the temperature distribution becomes symmetrical with respect to the line connecting the centers of the evaporator and the condenser. It is considered that the vapor separates at the evaporator and flows to the condenser in both directions at roughly equal rates. Results measured at points 3 and 4 also confirm the understanding that the cold fluid takes the shortest path from the condenser to the evaporator. Consequently, the circulating direction was decided by setting the evaporator asymmetric with respect to the condenser.

Direct-Cooling Configuration

Two pipe configurations were tested: 1) a single-looped pipe and 2) a dual-looped pipe. The dual-looped pipe was able to provide higher heat fluxes.

Single-Looped Pipe

The single-looped pipe is shown in Fig. 9. The i.d. of the pipe was also 2 mm, but 320 mm long. The working fluid occupied 40% of the internal volume as indicated by the results of indirect-cooling experiments. The flow direction of the working fluid was set by locating the evaporator asymmetrically to the line A-A'.

Dual-Looped Pipe

The dual-looped pipe is shown in Fig. 10. Based on the results of the indirect cooling experiment, the working fluid was set at 40% of the internal volume. Part of the pipe between the evaporator and the condenser (path m-n) was attached to the outer surface of the evaporator as shown in the

Table 1 Temperature of the pipe vs the location of the heater

	Heater location				
Unit: °C	1	2	3	4	5
a	50.2	54.6	50.2	60.3	45.6
b	43.9	43.7	29.6	56.3	36.0
c	26.9	27.0	26.1	30.0	26.2
d	28.0	24.3	22.9	24.8	23.0
e	38.4	47.5	35.1	36.2	29.9
f	47.2	70.3	42.0	46.9	41.9
g	48.7	60.2	49.8	75.9	52.9
h	48.1	60.2	65.4	67.6	57.2

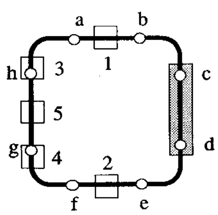

Fig. 8 The temperature measurement points and heater locations.

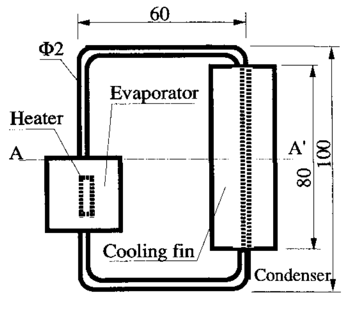

Fig. 9 Single looped pipe.

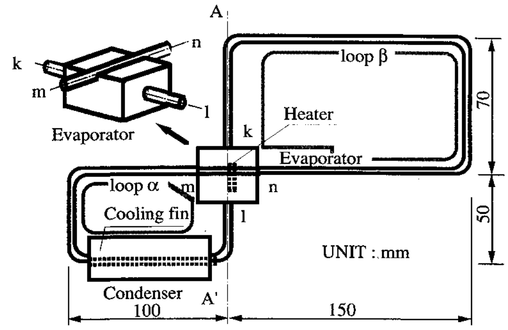

Fig. 10 Dual-looped capillary pipe.

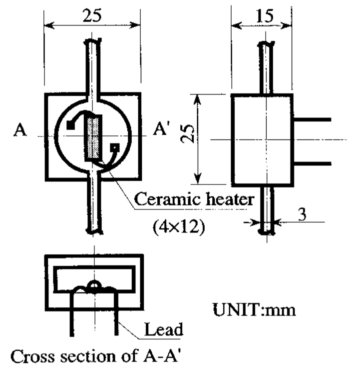

Fig. 11 Structure of the evaporator.

inset to Fig. 10 to increase the circulation rate of the working fluid by reboiling some of the fluid and, thus, decreasing the overall resistance to mass flow. Loop a was smaller than loop b to ensure forced circulation by establishing inequal partial liquid distribution. The condenser section was located in loop a as this location strongly favored the return of the liquid to the evaporator.

Evaporator and Setup

A ceramic heater simulated a FET chip with a generation area of 4 × 12 mm. The heater, installed in the evaporator section, was immersed in the working fluid. The evaporator was connected to the capillary looped pipe. The heat generation rate was controlled so that the heater's temperature did not exceed 100°C. The evaporator section is shown in detail in the inset to Fig. 11. The temperature of the heater in the direct-cooling experiment was determined beforehand as a function of its resistance. The cooling fins of the pipes were set on the fixture shown in Fig. 2. The pipes were tested using the same apparatus and procedure as used to test the indirect-cooling configurations.

Results on Direct-Cooling Looped Pipes

Single-Looped Pipe

The temperature of the single-looped pipe is shown in Fig. 12. The temperatures were measured on the outside wall of

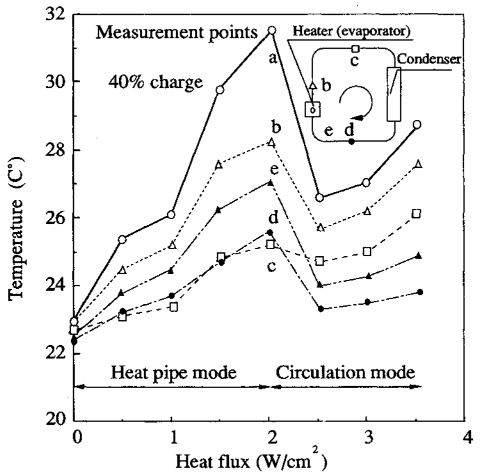

Fig. 12 Temperatures of the single-looped pipe (direct-cooling type) vs heat flux.

the pipe and the evaporator. At heat fluxes of 2 W/cm^2 or less, the temperatures at points b and e are higher than those at points c and d. In addition, the temperature at point c is roughly equivalent to the temperature at point d. Thus, the vapor flows from the evaporator in both directions, and condenses at points c and d. However, the temperatures at points b and c are higher than the values at d and e at a heat flux of 3 W/cm^2. In addition, the temperatures at points a and e are lower than those at a flux of 2 W/cm^2. These experimental results show that at high fluxes the condensed liquid flows into the evaporator through point e, and the vapor transfers the latent heat flowing from the evaporator to the condenser through points b and c at low fluxes.

Although the exact reason why the flow regime changes at the heat flux of 3 W/cm^2 is not clear, we assume the following.

When the Heat Flux is 2 W/cm^2 or Less

As the vapor generated in the evaporator passes through the upper half of the pipe, it condenses to a liquid and accumulates in the bottom half of the pipe. The vapor generated in the evaporator section flows in both directions from point a to point c, and from point e to point d. The condensed liquid is returned to the evaporator by mass flow in both directions in the heat pipe mode.

When the Heat Flux is 3 W/cm^2 or More

As the amount of vapor increases, the length of stagnate liquid in the pipe next to the cooling fin gradually shortens. Since the diameter of the pipe is small, the liquid returns to the evaporator in the slug flow regime due to the action of the capillary force between the pipe wall and the liquid. The flow direction is determined by the pressure drop caused by the frictional force between the pipe and the fluid, and the fluid circulates in the direction in which the pressure drop is the lowest. Therefore, the vapor flows in a clockwise direction, and is condensed under the cooling fin. The condensed liquid returns to the evaporator in the same clockwise direction. This is equivalent to the circulation mode.

A comparison of the thermal conductance of the heat pipe and circulation modes is shown in Fig. 13. In the figure, the horizontal axis is the temperature difference between the evaporator and the condenser, and the vertical axis is the heat input rate. The gradients of the straight lines are values of the thermal conductance between the evaporator and the condenser. This figure shows that the thermal conductance of the circulation mode is 2 times greater than that of the heat pipe mode.

Dual-Looped Pipe

The temperature of the dual-looped pipe is shown in Fig. 14. The temperatures at points b and d are higher than those at points c and e at heat fluxes of 3 W/cm^2 or less.

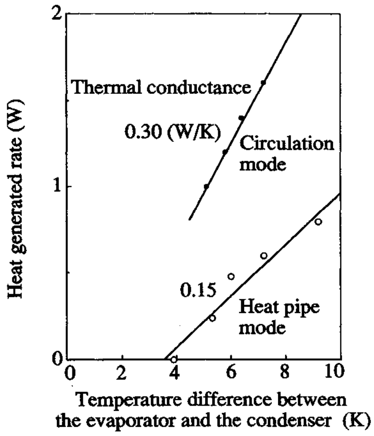

Fig. 13 Thermal conductance for the single-looped pipe.

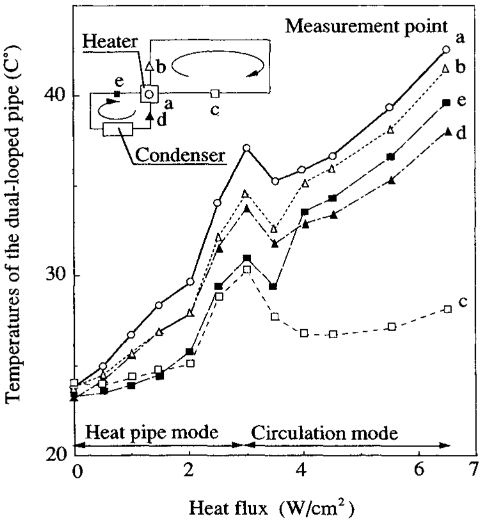

Fig. 14 Temperature of the dual-looped pipe (direct-cooling type) vs heat flux.

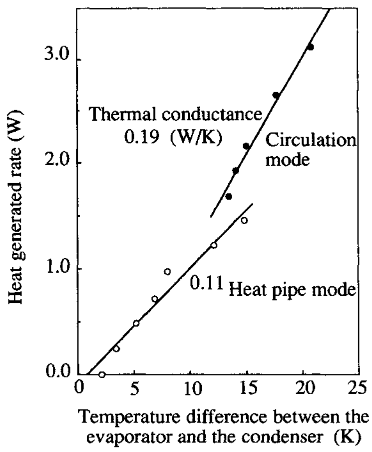

Fig. 15 Thermal conductance for the dual-looped pipe.

Since the temperatures at points b and d are the same, the vapor from the evaporator flows in both directions. The vapor also flows towards c and e because the temperature measured at point c equals that at point e. However, when the heat flux is 4 W/cm^2 or more, the operation of the fluid is changed to the circulation mode since the temperature at point e is higher than that of point c. In particular, the temperature at c does not increase at a heat flux of 3 W/cm^2 or more compared to the response at lower heat fluxes. Therefore, we feel that the dual-looped pipe works in the heat pipe mode at heat fluxes of 3 W/cm^2 or less, but changes to the circulation mode when the heat flux is above 3 W/cm^2. A comparison of the thermal conductance of the heat pipe and the circulation modes is shown in Fig. 15. The thermal conductance of the circulation mode is about twice that of the heat pipe mode. Figure 15 shows that the dual-looped pipe supports heat fluxes that are about twice those supported by the single-looped pipe shown in Fig. 13. Therefore, the dual-looped pipe operates as two single-looped pipes connected in series.

Comparison of Heat Transport with Direct Cooling and Indirect Cooling

In the case of the single-looped pipe, comparing direct cooling with indirect cooling, the mean thermal conductances are 0.49 (W/K) and 0.16 (W/K), respectively. Therefore, the thermal conductance with direct cooling is about 3 times greater than that with indirect cooling.

Conclusions

The circulating direction and reasonable liquid charge quantity were obtained for a direct-cooling single capillary looped pipe. In addition, the temperature profiles and thermal conductances for direct-cooling single and dual-loop pipes were obtained from experiments. The results are as follows:

1) The circulating direction can be set by placing the evaporator asymmetrical to the condenser.
2) A 40% liquid charge (HCFCs 142b) yielded the highest overall thermal conductance.
3) It was found that the flow regime changes when the heat flux increases. The heat pipe mode changes to the circulation mode.
4) The thermal conductance between the evaporator and the condenser in the circulation mode is twice that in the heat pipe mode.
5) The dual-looped pipe operates as two single-looped pipes connected in series at high heat fluxes.

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